GEOLOGY | THE GEOLOGICAL SOCIETY OF AMERICA®

https://doi.org/10.1130/G52232.1

Manuscript received 28 May 2024
Manuscript accepted 26 July 2024

Published online 19 August 2024

Double subduction controls on long-lived continental tectonics and subcontinental mantle temperatures

Lin-Sen Li[1,2], Fabio A. Capitanio[2], Peter A. Cawood[2], Ben-Jun Wu[1,*], Ming-Guo Zhai[1,3], and Xiao-Lei Wang[1,*]

[1]State Key Laboratory for Mineral Deposits Research, School of Earth Sciences and Engineering, Nanjing University, Nanjing 210023, China

[2]School of Earth Atmosphere and Environment, Monash University, Clayton, Victoria 3800, Australia

[3]Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China

ABSTRACT

The complexities of convergent margins commonly include the interactions of subduction zones, with many geological records of "double" subduction. Here, we build two-dimensional numerical models to explore the evolution of complex subduction systems by systematically testing single and inward-dipping double subduction beneath a continental upper plate and the impact of continental collision on these systems. When compared to single subduction models, the inward-dipping double subduction shows hindered trench migrations and larger volumes of upwelling mantle enhanced by excess sinking slab mass. Double subduction draws larger volumes of hotter mantle beneath the continent in an area much broader than the marginal basins of single subductions, contributing to subcontinental heating by ~200 °C. As collision jams one margin of a double subduction system, the other margin follows the evolution of migrating single subduction zones, although characterized by persisting higher mantle temperatures and strong upwellings, inherited from the double subduction stage, and large-scale upper plate extension. The modeling outcomes are compared to scaling arguments to test the viability of the mechanism proposed for tectonics of the Cenozoic South China Sea and Neoproterozoic Yangtze Block (southeastern China), where the inward-dipping double subduction provides a context for protracted large-scale continental extension, hotter subcontinental temperatures, and channeled mantle flow not easily reconciled with the dynamics of single subduction zones.

INTRODUCTION

The spatial and temporal evolution of plate boundaries on modern Earth comprises many examples of subduction zones that became close enough to interact. The South China Sea is one of the largest sea basins along the margin of the Eurasian continent, formed above an early Cenozoic inward-dipping double subduction system involving the Pacific, Philippine Sea, and Indo-Australian Plates (Fig. 1A; Lin et al., 2019). Here, tomographic and geochemical evidence shows the upwelling Hainan plume constrained and deflected by the surrounding subduction system (Wang et al., 2013; Zhang and Li, 2018), which might have contributed to the opening of the South China Sea (Flower et al., 1998). A similar situation may have impacted the Neoproterozoic evolution of the Yangtze Block (southeastern China), with evidence for an inward-dipping double subduction system, involving two subduction zones dipping toward the Yangtze Block from both sides, that terminated with assembly of the Cathaysia Block and associated high-temperature melting and large-scale (>500 km) rifting (Fig. 1B; Li et al., 1999; Zhou et al., 2002; Gao et al., 2016). However, the anomalously high temperatures and width of the extensional tectonics are not easily explained by temperatures and size of modern marginal basins; therefore, the interpretation of this case remains controversial.

Here, we focus on the evolution of inward-dipping double subduction and show how it differs from that of single subduction zones in terms of operational scales and the role of the lower mantle (Holt et al., 2017). Models of double subduction have primarily focused on the same dipping systems, where two subduction zones form with both slabs dipping in the same direction (e.g., Pusok and Stegman, 2020), showing how adjacent slabs mutually influence each other (e.g., Király et al., 2016, 2021) and result in large-scale tectonics shaping continents (Jagoutz et al., 2015; Pusok and Stegman, 2020). Similar large-scale extension occurs in inward-dipping double subduction zones due to the retreat of diverging trenches, although in these systems the focused slab mass increases the volume and vigor of mantle upwelling (Lyu et al., 2019; Dasgupta and Mandal, 2022; Lei and Davies, 2023).

We propose a systematic test of how the dynamics and long-term evolution of inward-dipping double subduction differs from those of single systems. We use thermomechanical computational modeling of inward-dipping double subduction systems to address the characteristics of mantle temperature and ensuing tectonics over ~100 m.y. and illustrate the long-lasting impact on mantle flow and tectonics exceeding the lifespan of double subduction, with high temperatures and large-scale extension sustained when collision jams one of the margins and the other evolves as a single subduction. The results shed light on the evolution of the Cenozoic South China Sea and Neoproterozoic Yangtze Block.

MODEL SETUP AND RESULTS

To test quantitatively the thermomechanical evolution of double subduction systems, we used the geodynamic modeling framework

Xiao-Lei Wang https://orcid.org/0000-0002-5115-7804
*wxl@nju.edu.cn; benjunwu@nju.edu.cn

CITATION: Li, L.-S., et al., 2024, Double subduction controls on long-lived continental tectonics and subcontinental mantle temperatures: Geology, v. 52, p. 836–840, https://doi.org/10.1130/G52232.1

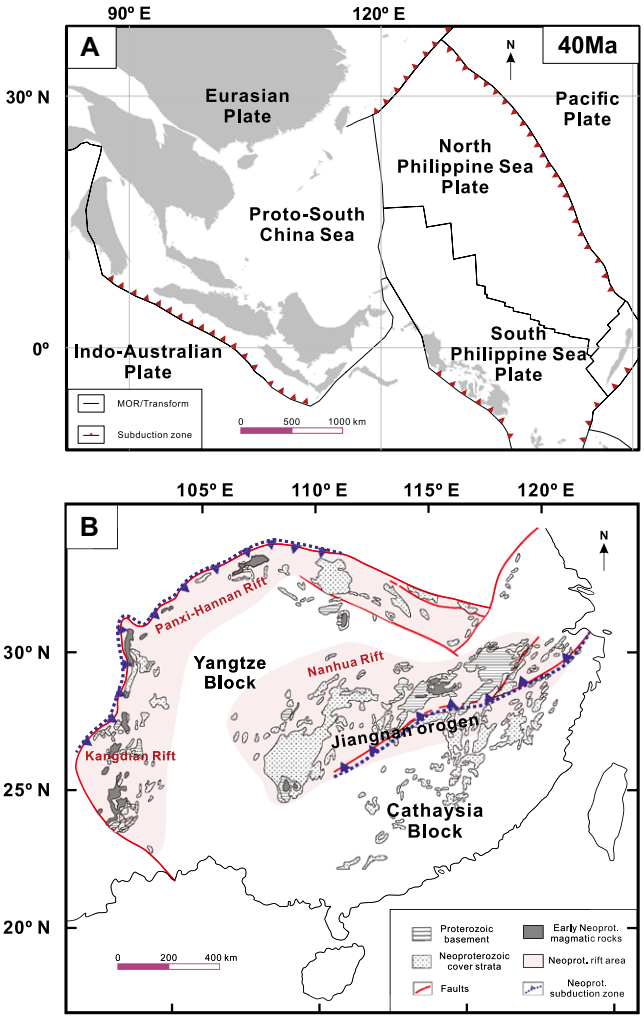

Figure 1. Integrated geological records related to two double-sided subduction systems. (A) reconstruction of South China Sea area by 40 Ma (Zahirovic et al., 2014). (B) Yangtze Block (southeastern China) with Proterozoic structures. MOR—mid-ocean ridge; Neoprot.—Neoproterozoic.

Underworld2 (Mansour et al., 2020). A full explanation of the governing equations and constitutive laws adopted is given in the Supplemental Material[1]. Our models investigate the evolution of inward-dipping double subduction systems and the influence of a collision of an exotic continental block. To compare to the geological cases presented, we use present-day mantle potential temperatures of 1350 °C and that inferred for the Neoproterozoic of 1450 °C (Herzberg et al., 2010). All models have a continental upper plate in the center that is 120 km thick, including 35 km crust and an optional weak zone that accommodate strains, bounded by two inward-dipping subducting oceanic slabs, each 70 km thick, comprising 10 km crust. The exotic block has the same properties as the continent. The modeled space includes the lower mantle, differentiated by increased density and viscosity. See Figure S1 and Tables S1 and S2 in the Supplemental Material for the configuration and setup of the models.

The modeling is designed to reveal key features of an inward-dipping double subduction system by comparing models with increasing complexities. We first present the evolution of single subduction systems, representing the ongoing subduction of an oceanic slab, and how this is affected by the collision of an exotic block. Then we show the evolution of double systems by adding a second subducting slab that dips beneath the opposite side of the continent and show the termination of one of the subduction zones by collision of an exotic block.

Single Subduction System

The single subduction (SS) system provides a reference model. The slab subducts at a steep angle then slows down as it accumulates atop the lower mantle until penetrating deeper. A wide flow cell forms as the slab descends and the mantle upwells (Fig. 2A), driving upper plate drift (Fig. 3A) in response to slab migration. The strain rate map indicates compression at the margin with limited extension in a back-arc region <400 km wide (Fig. 3B).

Models of single subduction with collision (SC) show a similar evolution to the SS models until exotic block entrainment leads to a staged evolution (Fig. 2B). Subduction in the initial stage (Stage I) does not differ from that of previous models as the exotic block approaches. Upon collision, subduction slows down and eventually ceases after a portion of the buoyant block has subducted (Stage II; Fig. 3C). As tensile stresses exceed the lithospheric strength, the oceanic slab detaches, then surface motions vanish while the detached slab sinks (Stage III; Fig. 3D). The vertical mantle flow velocity measured beneath the plates and the strain rates (Figs. 3C and 3D) show that the flow changes from that dominated by subduction, with a wide but weak upwelling, due to slab sinking, to smaller-scale convection, indicated by weaker drips and lower surface strain rates. In this stage, trench motion becomes rather stationary, and the heating beneath the continent in single systems (dashed lines in Fig. 3I) is negligible.

Double Subduction System

Models for the evolution of double subduction (DS) systems exhibit a combination of features observed in SS models and those unique to DS. Subduction rates and slab morphology of inward-dipping double subduction zones are nearly symmetrical (Fig. 2C). As the two slabs reach the transition zone, they restrict mantle circulation and substantially enhance upwelling beneath the upper plate (Fig. 3E). The upward flow is more vigorous and extended compared to that in the SS model, with velocity >2 cm/yr faster than that of the single subduction zone, over an area >1000 km wide, significantly broader than the <400 km of an SS model's back arc. The coupling with enhanced mantle flow results in higher strain rates in the upper plate, leading to extension over a broader area than in typical marginal basins (Fig. 3F).

The double subduction with collision (DC) models show a complex evolution (Fig. 2D). While Stage I mostly resembles that of DS models (Fig. 3G), in Stage II, the right-hand subduction is jammed by buoyant block entrainment, allowing the free migration of the subduction margin, with shallow slab and upper plate drift (Fig. 3G). Stage III starts upon the slab detachment from the accreted continental block. In this stage, the mantle rearranges to smaller-scale flow, as in the SC model; however, the upwelling due to the still-sinking slab remains extensive and vigorous (Fig. 3G), with upper plate extension increasing from strain rates of $\sim 2 \times 10^{-16}$ s^{-1} in Stage I to $\sim 5 \times 10^{-16}$ s^{-1} in Stage III (Fig. 3H). In summary, as collision jams one of margins, the other subducting margin is free to evolve in a similar way to that of SS systems; however, the driving forces are enhanced by the excess

[1]Supplemental Material. Model parameters and methods, Figures S1–S7, Tables S1–S2, and Movies S1–S2. Please visit https://doi.org/10.1130/GEOL.S.26415856 to access the supplemental material; contact editing@geosociety.org with any questions.

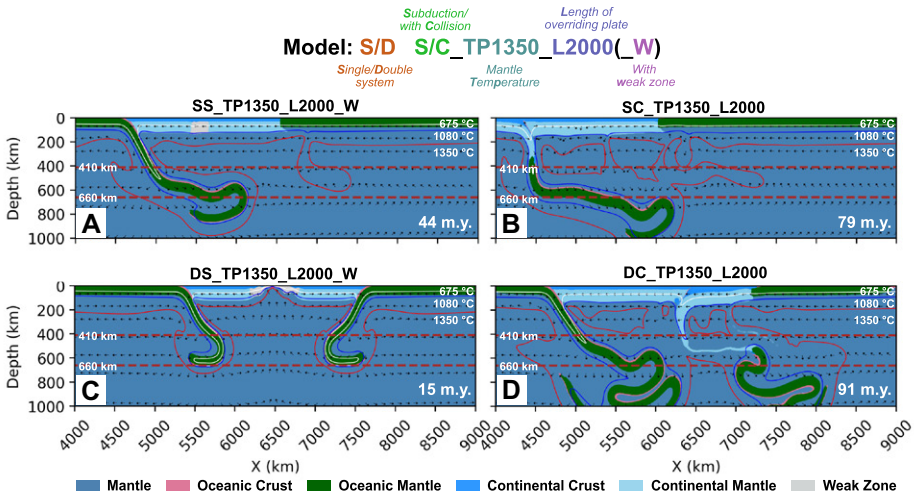

Figure 2. Snapshots of tested model cases. Arrows indicate velocity direction over time. Model setup is in Figure S1 (see text footnote 1).

slab mass of the ceased one, still in the mantle, enhancing the width and vigor of the mantle flow and surface strain.

The rearrangement of mantle flow in double subduction systems results in significant heating beneath the upper plate (solid lines in Fig. 3I), in contrast to that observed in single subduction systems. The combined effect of two slabs, enhanced upwellings, and thermal insulation of the mantle (gray area in Fig. 3I) leads to pronounced subcontinental heating. For mantle potential temperatures of 1450 °C and 1350 °C, asthenosphere temperature increases by as much as ~200 °C and ~180 °C, respectively (Fig. 3I). Heating decreases with a wider upper plate of 4000 km, achieving an increase of only ~100 °C (Fig. 4A). These effects are explored in the next section in comparison with proposed scaling laws.

DISCUSSION

Large-Scale, Long-Lasting Effects of Inward-Dipping Double-Sided Subduction

Comparisons between single and double subduction systems reveal similar back-arc extension; however, the excess slab mass in the mantle for the double subduction scenarios enhances the scale of the mantle flow, drawing an increase of mantle temperature to ~200 °C, beneath an upper plate with a width of >1000 km, potentially leading to protracted extension over similar scales.

These effects are influenced by the scale of upper plate and mantle temperature as well as the geometry of the double subduction zone (Fig. 4A). Our choice of two-dimensional space for the models simplifies realistic mantle circulations, though it maximizes confinement as in previously published efforts (Pusok and Stegman, 2020; Lei and Davies, 2023). This limitation is overcome by comparing results with a scaling analysis proposed by Le Pichon et al. (2021) to emphasize the role of the geometry on confinement and mantle temperature. The scaling allows us to test our models for an increased mantle temperature and wider upper plate, thus validating the results of our work. The increased mass of neighboring slabs enhances the scale of the mantle flow and thermal insulation in the asthenosphere, which is inversely proportional to the width of the upper plate, with temperature rises of >100 °C for an upper plate of width <4000 km, though this scaling may not apply to very narrow systems due to instability from strong slab interactions (e.g., Zhang et al., 2024). This scaling is found in previous works, showing increased stress as a result of approaching slabs (Király et al., 2016, 2021), increased thermal insulation due to inhibited lateral flow (Coltice et al., 2007; Lenardic et al., 2011), as well as enhanced upwelling and large-scale extension above an inward-dipping double subduction zone (Holt et al., 2017; Lyu et al., 2019; Dasgupta and Mandal, 2022; Lei and Davies, 2023), supporting the idea of viscous stresses and asthenosphere heating enhanced by confined mantle.

Our models highlight that the effect of double subduction on system features such as

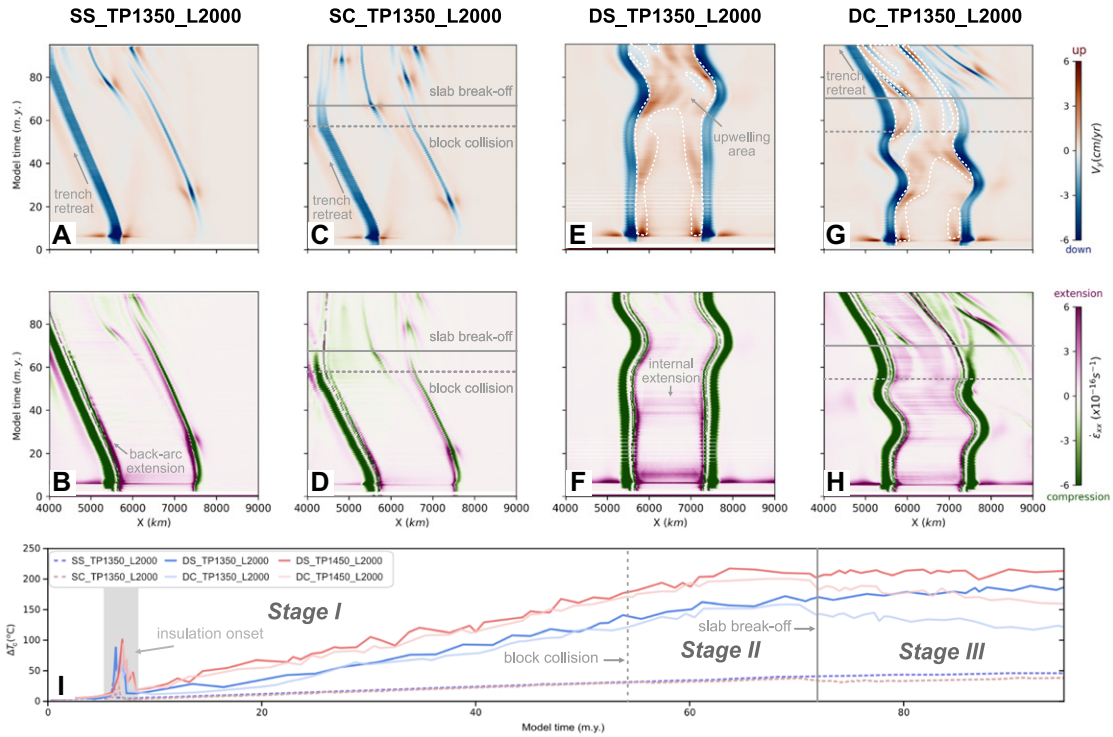

Figure 3. (A–H) Evolutions across tested model cases of vertical velocity component v_y at 200 km depth in asthenosphere (first row) and horizontal strain rate field $\dot{\varepsilon}_{xx}$ at 100 km depth in lithosphere (second row). (I) Temperature rises in subcontinental mantle (ΔT_c) measured against suboceanic values. See Figure 2 for key to model naming.

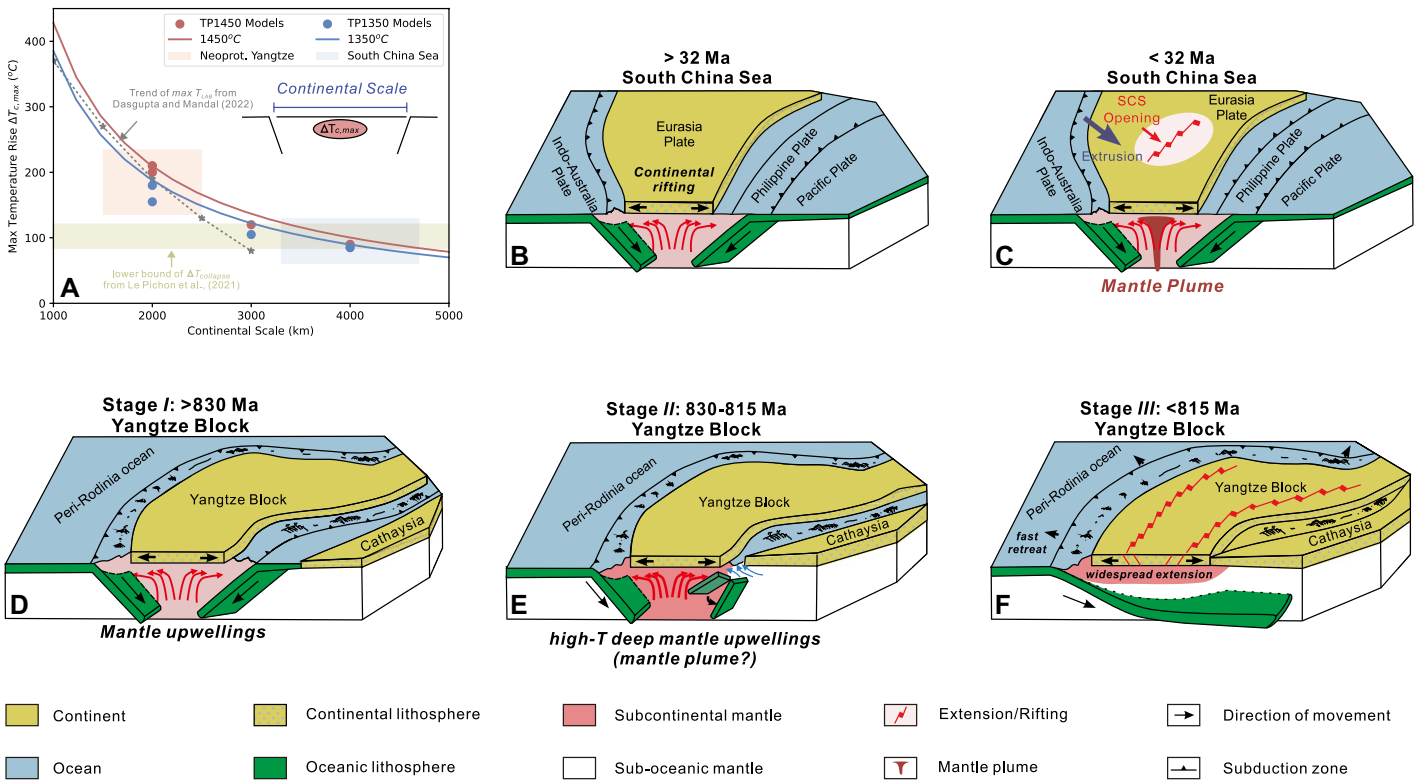

Figure 4. Scaling results (A) with sketch of the evolution of South China Sea (B, C) and Neoproterozoic Yangtze Block (D–F). As shown in (A), continental scale and $\Delta T_{c,max}$ denote the distance between two inward-dipping subduction zones across the continents and the maximum temperature rise in the subcontinental mantle, respectively. The red and blue lines in (A) represent the scaling results for mantle temperatures at 1450°C and 1350°C, respectively. Shaded areas outline the estimates of maximum subcontinental temperatures in the Neoproterozoic Yangtze block and the Cenozoic South China Sea, based on their continental scale. The legends for (B–F) are shown at the bottom. See Supplemental Material (text footnote 1) for scaling details. T_{LAB}—temperature measured at the Lithosphere-Asthenosphere Boundary; $\Delta T_{collapse}$—the lateral upper mantle temperature difference for girdle collapse; SCS—South China Sea.

the broad scale of asthenospheric heating and large-scale extension persist even when one of the two slabs breaks off. This reflects the sinking of excess slab, which eventually penetrates the lower mantle after one subduction zone has ceased. Such large-scale effects of the deep sinking slabs agrees with wider and longer-lasting convective cells (Dal Zilio et al., 2018) and increased plate velocities beneath the Asia-India collision (Jagoutz et al., 2015) and southeast Asia margins (Yang et al., 2018), which cannot be reconciled with a shallow-single subduction system.

Geological Implications on the Evolution of Double-Sided Subduction Systems

Modern and inferred ancient examples of inward-dipping double-sided subduction are that of the early Cenozoic South China Sea region (Lin et al., 2019) and Neoproterozoic Yangtze Block (Zhou et al., 2002) and may be linked to the supercontinent cycle (e.g., Jellinek et al., 2020; Le Pichon et al., 2021, 2023).

Double subduction systems may have influenced large-scale tectonics of the South China Sea (Figs. 4B and 4C). Opening of the sea has been proposed to be a response to the extrusion of Indochina, triggered by the India-Asia collision (Briais et al., 1993). Yet, the timing of the extrusion (ca. 27–22 Ma) postdates the onset of the rifting (>32 Ma; Hsu et al., 2004). Alternatively, a mantle plume has been proposed to have driven the South China Sea opening (Flower et al., 1998), although the early record of the mantle plume is younger than the extrusion (ca. 24 Ma; Yu et al., 2018). We suggest that inward-dipping double subduction might have facilitated mantle upwellings and stretched a broad area over the continents, aligning with large-scale but weak extensions observed at the southeast Eurasian margins (Fig. S2; Zahirovic et al., 2014). Our model shows that, when scaled to the ~4000 km width of continents of the early stages of South China Sea rifting, such extension has been minor (Fig. S3). In the same way, this mechanism may have become pronounced as new subduction zones started later, which shorten the characteristic width between margins (e.g., Dasgupta and Mandal, 2022; Zhang et al., 2024). The deep double subduction in this region has been invoked to constrain mantle circulation and plume ascent (e.g., Wang et al., 2013). Our model reveals similar constraints on upwelling but across a broader scale and with heating under a double subduction system (~100 °C increase; Fig. 4A) that is modest compared to that from mantle plumes (~250 °C; Wang et al., 2012). In this scenario, the role of the hotter Hainan plume could explain the high-temperature melting that occurred after South China Sea opening (Zhao, 2001).

The mid-Neoproterozoic evolution of the Yangtze Block can be explained within the construct of a three-stage model of an inward-dipping double subduction, collision, and transition to single subduction (Figs. 4D–4F). The arc-type magmatism along the margins of the Yangtze Block before 830 Ma (Fig. 1B; Yao et al., 2019) indicates a long-term double subduction (Stage I). The amalgamation of Yangtze and Cathaysia Blocks at ca. 830–815 Ma is compatible with Stage II and lasts ~20 m.y. in models. Stage III follows the cessation of subduction along the southeastern margin of the Yangtze Block and a rapid retreat of western margin, increasing continental drift rates to 6–7 cm/yr or faster (Fig. S4C; Fu et al., 2022) and promoting the large-scale rifting represented by the Kangdian and Nanhua Rifts. Additionally, the notable granite emplacements in Stage II (Wang et al., 2014) were accompanied by the emergence of mantle-derived high-Mg basalts, requiring mantle heating by +260 ± 50 °C. Although a plume origin has been invoked for this heating (Wang

et al., 2007), our findings indicate that such temperature rises could be a characteristic of a hot Neoproterozoic mantle in response to double subduction (Fig. 4A).

A comparison of numerical models with early Cenozoic and Neoproterozoic examples of inward-dipping double subduction systems shows that increased slab mass and constrained mantle flow can trigger large-scale upwelling and widespread stretching. This setting may explain the large-scale stretching in the South China Sea, bordered by inward-dipping subduction zones, the deflection of the Hainan plume, and similar tectonic process to the Neoproterozoic Yangtze Block. In the hotter Neoproterozoic mantle, asthenospheric heating is higher than that of today, providing a mechanism for preserved igneous activity related to high-temperature melting. We show that such large-scale flow and tectonics may persist for a considerable time after the systems evolve from a double to a single subduction system.

ACKNOWLEDGMENTS

This work was financially supported by the National Natural Science Foundation of China (no. 42025202 and 42374112), a scholarship from China Scholarship Council (no. 202206190071), Frontiers Science Center for Critical Earth Material Cycling, and Australian Research grant FL160100168. Reviews by editor Urs Schaltegger, Mark Jellinek, and four anonymous reviewers are gratefully acknowledged.

REFERENCES CITED

Briais, A., Patriat, P., and Tapponnier, P., 1993, Updated interpretation of magnetic anomalies and seafloor spreading stages in the South China Sea: Implications for the Tertiary tectonics of Southeast Asia: Journal of Geophysical Research, v. 98, p. 6299–6328, https://doi.org/10.1029/92JB02280.

Coltice, N., Phillips, B.R., Bertrand, H., Ricard, Y., and Rey, P., 2007, Global warming of the mantle at the origin of flood basalts over supercontinents: Geology, v. 35, p. 391–394, https://doi.org/10.1130/G23240A.1.

Dal Zilio, L., Faccenda, M., and Capitanio, F., 2018, The role of deep subduction in supercontinent breakup: Tectonophysics, v. 746, p. 312–324, https://doi.org/10.1016/j.tecto.2017.03.006.

Dasgupta, R., and Mandal, N., 2022, Role of double-subduction dynamics in the topographic evolution of the Sunda Plate: Geophysical Journal International, v. 230, p. 696–713, https://doi.org/10.1093/gji/ggac025.

Flower, M., Tamaki, K., and Hoang, N., 1998, Mantle extrusion: A model for dispersed volcanism and DUPAL-like asthenosphere in East Asia and the western Pacific, *in* Flower, M.F.J., et al., eds., Mantle Dynamics and Plate Interactions in East Asia: American Geophysical Union Geodynamics Series 27, p. 67–88.

Fu, H., Zhang, S., Condon, D.J., and Xian, H., 2022, Secular change of true polar wander over the past billion years: Science Advances, v. 8, https://doi.org/10.1126/sciadv.abo2753.

Gao, R., et al., 2016, SINOPROBE deep reflection profile reveals a Neo-Proterozoic subduction zone beneath Sichuan Basin: Earth and Planetary Science Letters, v. 454, p. 86–91, https://doi.org/10.1016/j.epsl.2016.08.030.

Herzberg, C., Condie, K., and Korenaga, J., 2010, Thermal history of the Earth and its petrological expression: Earth and Planetary Science Letters, v. 292, p. 79–88, https://doi.org/10.1016/j.epsl.2010.01.022.

Holt, A.F., Royden, L.H., and Becker, T.W., 2017, The dynamics of double slab subduction: Geophysical Journal International, v. 209, p. 250–265, https://doi.org/10.1093/gji/ggw496.

Hsu, S.-K., Yeh, Y.-C., Doo, W.-B., and Tsai, C.-H., 2004, New bathymetry and magnetic lineations identifications in the northernmost South China Sea and their tectonic implications: Marine Geophysical Researches, v. 25, p. 29–44, https://doi.org/10.1007/s11001-005-0731-7.

Jagoutz, O., Royden, L., Holt, A.F., and Becker, T.W., 2015, Anomalously fast convergence of India and Eurasia caused by double subduction: Nature Geoscience, v. 8, p. 475–478, https://doi.org/10.1038/ngeo2418.

Jellinek, A.M., Lenardic, A., and Pierrehumbert, R.T., 2020, Ice, fire, or fizzle: The climate footprint of Earth's supercontinental cycles: Geochemistry, Geophysics, Geosystems, v. 21, https://doi.org/10.1029/2019GC008464.

Király, Á., Capitanio, F.A., Funiciello, F., and Faccenna, C., 2016, Subduction zone interaction: Controls on arcuate belts: Geology, v. 44, p. 715–718, https://doi.org/10.1130/G37912.1.

Király, Á., Funiciello, F., Capitanio, F.A., and Faccenna, C., 2021, Dynamic interactions between subduction zones: Global and Planetary Change, v. 202, https://doi.org/10.1016/j.gloplacha.2021.103501.

Lei, Z., and Davies, J.H., 2023, Progressive weakening within the overriding plate during dual inward dipping subduction: Tectonophysics, v. 863, https://doi.org/10.1016/j.tecto.2023.230004.

Lenardic, A., Moresi, L., Jellinek, A.M., O'Neill, C.J., Cooper, C.M., and Lee, C.T., 2011, Continents, supercontinents, mantle thermal mixing, and mantle thermal isolation: Theory, numerical simulations, and laboratory experiments: Geochemistry, Geophysics, Geosystems, v. 12, https://doi.org/10.1029/2011GC003663.

Le Pichon, X., Jellinek, M., Lenardic, A., Şengör, A.M.C., and İmren, C., 2021, Pangea migration: Tectonics, v. 40, https://doi.org/10.1029/2020TC006585.

Le Pichon, X., Şengör, A.M.C., Jellinek, M., Lenardic, A., and İmren, C., 2023, Breakup of Pangea and the Cretaceous Revolution: Tectonics, v. 42, https://doi.org/10.1029/2022TC007489.

Li, Z.X., Li, X.H., Kinny, P.D., and Wang, J., 1999, The breakup of Rodinia: Did it start with a mantle plume beneath South China?: Earth and Planetary Science Letters, v. 173, p. 171–181, https://doi.org/10.1016/S0012-821X(99)00240-X.

Lin, J., Xu, Y., Sun, Z., and Zhou, Z., 2019, Mantle upwelling beneath the South China Sea and links to surrounding subduction systems: National Science Review, v. 6, p. 877–881, https://doi.org/10.1093/nsr/nwz123.

Lyu, T., Zhu, Z., and Wu, B., 2019, Subducting slab morphology and mantle transition zone upwelling in double-slab subduction models with inward-dipping directions: Geophysical Journal International, v. 218, p. 2089–2105, https://doi.org/10.1093/gji/ggz268.

Mansour, J., Giordani, J., Moresi, L., Beucher, R., Kaluza, O., Velic, M., Farrington, R., Quenette, S., and Beall, A., 2020, Underworld2: Python geodynamics modelling for desktop, HPC and cloud: The Journal of Open Source Software, v. 5, https://doi.org/10.21105/joss.01797.

Pusok, A.E., and Stegman, D.R., 2020, The convergence history of India-Eurasia records multiple subduction dynamics processes: Science Advances, v. 6, https://doi.org/10.1126/sciadv.aaz8681.

Wang, X.-C., Li, X.-H., Li, W.-X., and Li, Z.-X., 2007, Ca. 825 Ma komatiitic basalts in South China: First evidence for >1500 °C mantle melts by a Rodinian mantle plume: Geology, v. 35, p. 1103–1106, https://doi.org/10.1130/G23878A.1.

Wang, X.-C., Li, Z.-X., Li, X.-H., Li, J., Liu, Y., Long, W.-G., Zhou, J.-B., and Wang, F., 2012, Temperature, pressure, and composition of the mantle source region of late Cenozoic basalts in Hainan Island, SE Asia: A consequence of a young thermal mantle plume close to subduction zones?: Journal of Petrology, v. 53, p. 177–233, https://doi.org/10.1093/petrology/egr061.

Wang, X.-C., Li, Z.-X., Li, X.-H., Li, J., Xu, Y.-G., and Li, X.-H., 2013, Identification of an ancient mantle reservoir and young recycled materials in the source region of a young mantle plume: Implications for potential linkages between plume and plate tectonics: Earth and Planetary Science Letters, v. 377–378, p. 248–259, https://doi.org/10.1016/j.epsl.2013.07.003.

Wang, X.-L., Zhou, J.-C., Griffin, W.L., Zhao, G., Yu, J.-H., Qiu, J.-S., Zhang, Y.-J., and Xing, G.-F., 2014, Geochemical zonation across a Neoproterozoic orogenic belt: Isotopic evidence from granitoids and metasedimentary rocks of the Jiangnan orogen, China: Precambrian Research, v. 242, p. 154–171, https://doi.org/10.1016/j.precamres.2013.12.023.

Yang, T., Gurnis, M., and Zahirovic, S., 2018, Slab avalanche-induced tectonics in self-consistent dynamic models: Tectonophysics, v. 746, p. 251–265, https://doi.org/10.1016/j.tecto.2016.12.007.

Yao, J., Cawood, P.A., Shu, L., and Zhao, G., 2019, Jiangnan Orogen, South China: A ~970–820 Ma Rodinia margin accretionary belt: Earth-Science Reviews, v. 196, 102872, https://doi.org/10.1016/j.earscirev.2019.05.016.

Yu, M., Yan, Y., Huang, C.-Y., Zhang, X., Tian, Z., Chen, W.-H., and Santosh, M., 2018, Opening of the South China Sea and upwelling of the Hainan Plume: Geophysical Research Letters, v. 45, p. 2600–2609, https://doi.org/10.1002/2017GL076872.

Zahirovic, S., Seton, M., and Müller, R.D., 2014, The Cretaceous and Cenozoic tectonic evolution of Southeast Asia: Solid Earth, v. 5, p. 227–273, https://doi.org/10.5194/se-5-227-2014.

Zhang, N., and Li, Z.-X., 2018, Formation of mantle "lone plumes" in the global downwelling zone—A multiscale modelling of subduction-controlled plume generation beneath the South China Sea: Tectonophysics, v. 723, p. 1–13, https://doi.org/10.1016/j.tecto.2017.11.038.

Zhang, K., Liao, J., and Gerya, T., 2024, Onset of double subduction controls plate motion reorganisation: Nature Communications, v. 15, 1513, https://doi.org/10.1038/s41467-024-44764-8.

Zhao, D., 2001, Seismic structure and origin of hotspots and mantle plumes: Earth and Planetary Science Letters, v. 192, p. 251–265, https://doi.org/10.1016/S0012-821X(01)00465-4.

Zhou, M.-F., Yan, D.-P., Kennedy, A.K., Li, Y., and Ding, J., 2002, SHRIMP U–Pb zircon geochronological and geochemical evidence for Neoproterozoic arc-magmatism along the western margin of the Yangtze Block, South China: Earth and Planetary Science Letters, v. 196, p. 51–67, https://doi.org/10.1016/S0012-821X(01)00595-7.

Printed in the USA